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Green Evolution: Advancing Epoxy Composite Materials with Durian Peel Fiber Innovation

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Abstract

This study explores the transformative effects of treating durian peel fibers with $Ca(OH)_2$ solution and their subsequent application as a reinforcing agent in epoxy composite materials. Morphological and structural analyses reveal a notable improvement in compatibility and adhesion between treated fibers and epoxy resin, particularly at a 5 % $Ca(OH)_2$ concentration. Durian fruit peel, after being treated with clear lime water ($Ca(OH)_2$), is used to reinforce the epoxy composite material at the ratio of epoxy/durian fiber peel = 70/30. The results were established when durian peel fibers treated with 5 % lime water solution had the best mechanical properties (tensile strength: 65.68 MPa, flexural strength: 92.11MPa, compressive strength: 147.38 MPa, Izod impact strength: 9.07 kJ/m^2). In terms of fire retardancy, the best results were also obtained when reinforcing durian peel fibers treated with 5 % concentration of lime solution in $Ca(OH)_2$, specifically: Minimum oxygen index: LOI = 21.9 %, Burning speed according to UL 94: 20.66 mm/min. The structural morphology of the epoxy/durian peel fiber composite was evaluated using SEM. The results demonstrated good compatibility, with no evidence of layer exfoliation or phase separation at the epoxy resin-durian peel fiber interface when subjected to external forces. The results of the project indicate that epoxy composites reinforced with durian peel fibers hold great promise as a green, environmentally friendly material. By utilizing waste from the food industry, these composites offer potential applications across various fields, including the automotive, transportation, and construction industries.

Keywords: Epoxy, Composite materials, Durian peel fibers, Tensile strength, Flexural strength, Compressive strength, Izod impact strength, Minimum oxygen index, UL 94, Fire retardancy

Introduction

Ying-Chen's research group investigated new composites based on polypropylene (PP)/polylactic acid (PLA) matrix and bamboo fiber filler (BF) [1]. The resulting composite material brought about beneficial changes in morphology. Gamon *et al*. [2] also researched the fabrication of composite materials based on PLA with bamboo fibers. To improve the properties of the material, some research groups have manufactured PLA-based composite materials using nanocellulose fibers such as the research group Liu *et al.* [3] and Gapsari [4]. Some other studies have sought to modify the surface of banana fibers [5,6], lychee peels [7], and used coffee grounds [8] by using chemicals such as NaOH to strengthen the material epoxy resin-based composite material. Banana fibers after treatment with NaOH at concentrations of 1, 2, 3, 4 and 5 %. The results established with 5 % concentration of NaOH solution used to process banana fibers to reinforce PLA plastic are considered the best according to the research of Nguyen *et al.* [9]. In addition to bamboo fibers, banana fibers, used coffee grounds, lychee peels. Some projects have also researched reusing durian peels to reinforce composite materials on different plastic substrates. Aimi *et al.* [10] have researched the production of cellulose nanofibers from durian peel fiber (DSF) and reinforced PLA plastic. In addition, durian peel fibers are also incorporated into starch thermoplastics with different DPF contents (10, 20, 30, 40 and 50 % by weight) through compression molding process [11]. Thermal properties of the biocomposites improved with the addition of DPF, as evidenced by increased thermal stability of the material and indicated by a higher initial decomposition temperature. Charoenvai *et al*. [12] also researched the production of durian peel fiber to reinforce HDPE plastic-based composites with different weight content (5, 10, 15 and 20 %), research results showed that 10 % of durian peel fiber weight gives the best properties such as tensile strength, impact strength, and hardness. Alias et al. [13] studied the combination of durian peel fiber (DSF) with polymeric methane diphenyl diisocyanate (PMDI) at different ratios: DSF/6PMDI, DSF/8PMDI, and DSF/10PMDI (corresponding to 6%, 8%, and 10% PMDI resin, respectively) to produce sheet materials for use in the construction field. The research results indicated that 6% PMDI resin is the most suitable ratio. Gamay *et al*. [14] also have an overview article exploring the benefits, potential and value of durian pulp for food and other applications. In this review it was demonstrated that durian should not be thrown away as it has great potential in terms of added value to the product.

In the context of composite material development, the use of natural fibers has become a prominent trend due to sustainability and recyclability. Research by Nguyen *et al*. [15] indicates that using sugarcane bagasse and glass fibers to reinforce epoxy materials can significantly enhance mechanical properties and fire resistance. The results show that the optimal treatment concentration is 5 % lime solution, yielding a tensile strength of up to 295.08 MPa, flexural strength of 371.24 MPa, compressive strength of 255.39 MPa, and a LOI index of 29.8 %, meeting the V2 standard according to test method 94-V [15]. Alkali treatment has also been extensively studied to improve the properties of natural fibers. Vinod *et al*. [16] demonstrated that alkali treatment enhances the tensile strength of Ziziphus mauritiana fibers by up to 2.12 times and increases flexural strength by 1.38 times, while also improving sound absorption capabilities [16]. Similarly, research by Raharjo *et al*. [17] showed that treatment with calcium hydroxide not only increases the compatibility of zalacca fibers with the polymer matrix but also improves tensile strength and elastic modulus, with significant improvements observed after 24 h of treatment. Studies on fibers from Ficus macrocarpa bark indicate that alkali treatment can increase cellulose content from 48.4 to 59.7 %, while improving crystallinity index from 80.20 to 84.75 %. The maximum thermal degradation temperature of treated fibers reaches 378.87 °C, indicating high thermal stability [18]. Other research, such as that by Pokhriyal *et al*. [19], confirmed that alkali treatment on Himalayacalamus falconeri fibers not only increases tensile strength from 132 MPa to 196.5 MPa but also enhances thermal stability from 250 to 258 °C [19]. Investigation of the properties of Pennisetum orientale grass fibers shows that chemical treatment with alkali has increased cellulose content up to 65.1 % and reduced the crystallinity index from 42.92 to 62.02 nm, opening up possibilities for using this fiber in lightweight composite applications [20]. Cortaderia selloana grass fibers have also been confirmed to be usable as reinforcement material, with cellulose content reaching 53.7 wt.% and tensile strength of 20 ± 1.0 MPa [21].

Moreover, a review by Aravindh *et al.* [22] indicates that various chemical treatment techniques, particularly alkali treatment, can significantly enhance the physical and mechanical properties of composites made from natural fibers. Specifically, the study found that 5 % NaOH improves tensile strength and hardness while minimizing moisture absorption in the fibers [22]. Das *et al.* [23] evaluated jute/glass fiber-reinforced epoxy composites, showcasing superior physico-mechanical properties of hybrid composites. Their findings emphasized the importance of fiber-matrix interfacial adhesion, which was enhanced through chemical treatments, leading to improved hardness and mechanical performance [23]. Finally, research on roots from the Fragrant Screw Pine plant shows that cellulose can comprise up to 80.53 wt.%, with tensile strength ranging from 619 to 1038 MPa, highlighting their great potential in creating lightweight and durable composites [24]. In summary, improving the mechanical and thermal properties of composites made from natural fibers through chemical treatment methods is highly feasible and promises many future applications. These studies provide a solid foundation for the development of more sustainable and environmentally friendly composite materials.

From the above research works, it shows that durian notebooks have many uses, of which application in the manufacture of composite materials is a potential, because it can be applied in many industries such as: Multi-functional structures in industry automobiles, construction materials, transportation. Durian is the most popular seasonal fruit in Vietnam, but less than half of durians are consumed as food. Durian is a fruit with a high waste rate, becoming an environmental problem when thrown into landfills. Therefore, it is important to utilize durian waste as a potential natural fiber-based composite reinforcing material. Durian peel residue is recognized as one of the lignocellulosic materials with the potential to replace wood in the production of insulation panels. In this study, to improve the quality of durian peel fiber application in manufacturing epoxy resin-based composite materials, durian peel fibers were pre-treated with an environmentally friendly chemical, clear lime water ($Ca(OH)_2$) and the material was studied for structural morphology (SEM), mechanical properties, and fire retardant properties.

Materials and methods

Materials

Epikote 240 epoxy resin (EP) is a Bisphenol A-based epoxy resin supplied by Shell Chemicals (USA). It has an epoxy group content of 24.6%, an epoxy equivalent ranging from 185 to 196, and a viscosity of 0.7 to 1.1 Pa·s at 25 °C. Diethylenetriamine (DETA) supplied by Dow Chemicals (USA). NaOH provided by Dow Chemicals (USA. The coffee grounds raw material was collected from local coffee shops in the North Tu Liem district, Hanoi, Vietnam. $Ca(OH)_2$ (hydrated lime) can be purchased at building material stores in Bac Tu Liem district, Hanoi, Vietnam.

Characterizations

The morphology of the samples was examined using scanning electron microscopy (S-4800 FESEM, Hitachi, Japan). Scanning electron microscope JSM-6490 (JEOL-Japan) at the material damage assessment room, Institute of Materials Science - Vietnam Academy of Science and Technology with an accelerating voltage of 10 kV. Tensile strength was assessed following the ISO 527-1993 standard using an INSTRON 5582-100kN machine (USA) at a speed of 5 mm/min, maintaining a temperature of 25 °C and 75 % humidity. Flexural strength was evaluated per the ISO 178-1993 standard, utilizing an INSTRON 5582-100kN machine (USA) at a pulling speed of 5 mm/min, under conditions of 25 °C and 75 % humidity. Compressive strength was determined following the ISO 604-1993 standard using an INSTRON 5582-100kN machine (USA) with a tensile speed of 5 mm/min, at 25 °C and 75 % humidity. Izod impact strength was measured based on the ASTM D256 standard using a Tinius Olsen machine (USA).

The Limiting Oxygen Index (LOI) is utilized to determine the minimum oxygen concentration required in a nitrogen and oxygen mixture for a sample to burn under specific conditions, measured according to ASTM D2863 or JIS K7201 standards. The UL-94 test method, conducted on UL (Underwriters Laboratories) equipment, is employed to assess the relative flammability and dripping behavior of plastics. UL-94 comprises 3 different tests depending on the flammability classification (V0, V1, V2, HB, 5VA and 5VB). UL-94 testing is conducted following ASTM D635 and ASTM D586 standards.

The fracture toughness of composite materials is evaluated using the critical-stress intensity factor (KIC). Test samples were prepared as references, and the fracture toughness was assessed in accordance with ASTM D5045-99, employing a cross-head speed of 10 mm/min. The reported data represent the averages of 6 measurements, with each measurement exhibiting a deviation of ±5 %. The KIC values were determined using the following equations:

$$K_{IC} = \left(\frac{P_Q}{BW^{\frac{1}{2}}}\right) f(x)$$

$$f(x) = 6x^{1/2}\frac{(1.99 - x(1-x)(2.15 - 3.93x + 2.7x^2))}{(1+2x)(1-x^{\frac{3}{2}})} \quad (1)$$

where PQPQ represents the critical load for crack propagation (kN); BB denotes the specimen thickness (cm); Windicates the specimen width (cm); f(x)f(x) is the non-dimensional shape factor; aa is the crack length measured after the specimen has fractured (cm); and xx is the ratio of crack length to specimen width (calculated as x = a/Wx = a/W, with 0 < x < 10 < x < 1). The test specimens were created using silicon molds, which ensured a high degree of uniformity (**Figure 1**).

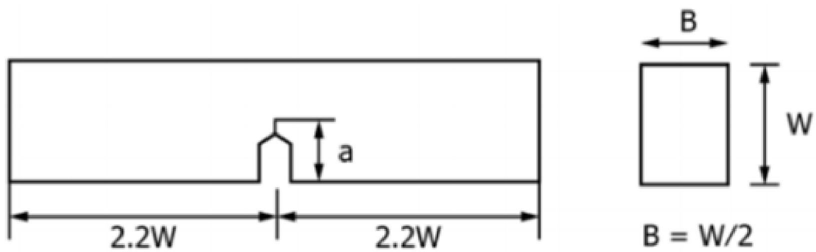


Figure 1 Three-point bending specimen configuration.

Sample manufacturing

Durian peel processing technique

The processing of durian peel is carried out through the following steps:

1) Preparation of raw material: Durian peels collected from Xuân Hòa commune are carefully inspected and selected, ensuring that only fresh and undamaged peels are used.

2) Washing: The durian peels are washed several times with clean water to remove dirt and impurities. Each washing session lasts about 15 min, and the water is changed for each wash to achieve optimal results.

3) Cutting: After washing, the durian peels are cut into small pieces approximately 2×2 cm^2 in size. This process is performed using a sharp knife to ensure uniformity in size.

4) Grinding: The cut pieces are then ground using a blender until a fine powder is achieved. This grinding process takes about 10 - 15 min, ensuring that the peels do not overheat.

5) Chemical treatment: The durian peel powder is soaked in a $Ca(OH)_2$ solution at various concentrations (3, 4, 5 and 6 %) for 3 days at room temperature (ranging from 27 to 30 °C). During the soaking period, the samples are gently stirred to ensure uniform treatment.

6) Washing and drying: After soaking, the powder is washed with water until a pH of 7 is reached to remove any residual chemicals. Subsequently, the samples are dried at 80 °C until a constant weight is achieved, usually taking between 24 to 48 h.

7) Sieving: Finally, the dried durian peel powder is sieved to obtain the desired fiber size, eliminating any larger particles that do not meet the requirements.

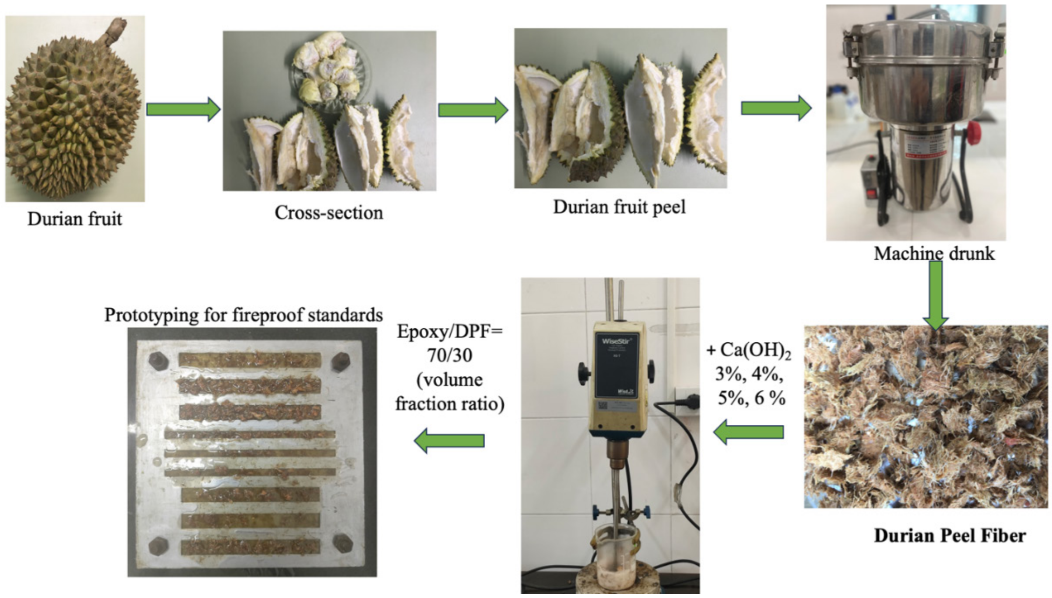


Figure 2 Manufacturing process of epoxy composite material reinforced with durian peel fibers.

These durian peel fibers were then used to reinforce epoxy composite materials, with an epoxy-to-fiber ratio of 70:30 by weight. The hardening agent used was Diethylenetriamine (DETA) at a concentration of 10 % by weight compared to the epoxy resin. The molding process was conducted on a metallic mold, providing mechanical and fire-resistant properties to the samples. After 24 h of drying at 80 °C for 3 h, and an additional 7 days for the samples to attain hardness, we removed the samples from the mold for further mechanical property assessments. The detailed procedure is depicted in **Figure 2**.

Results and discussion

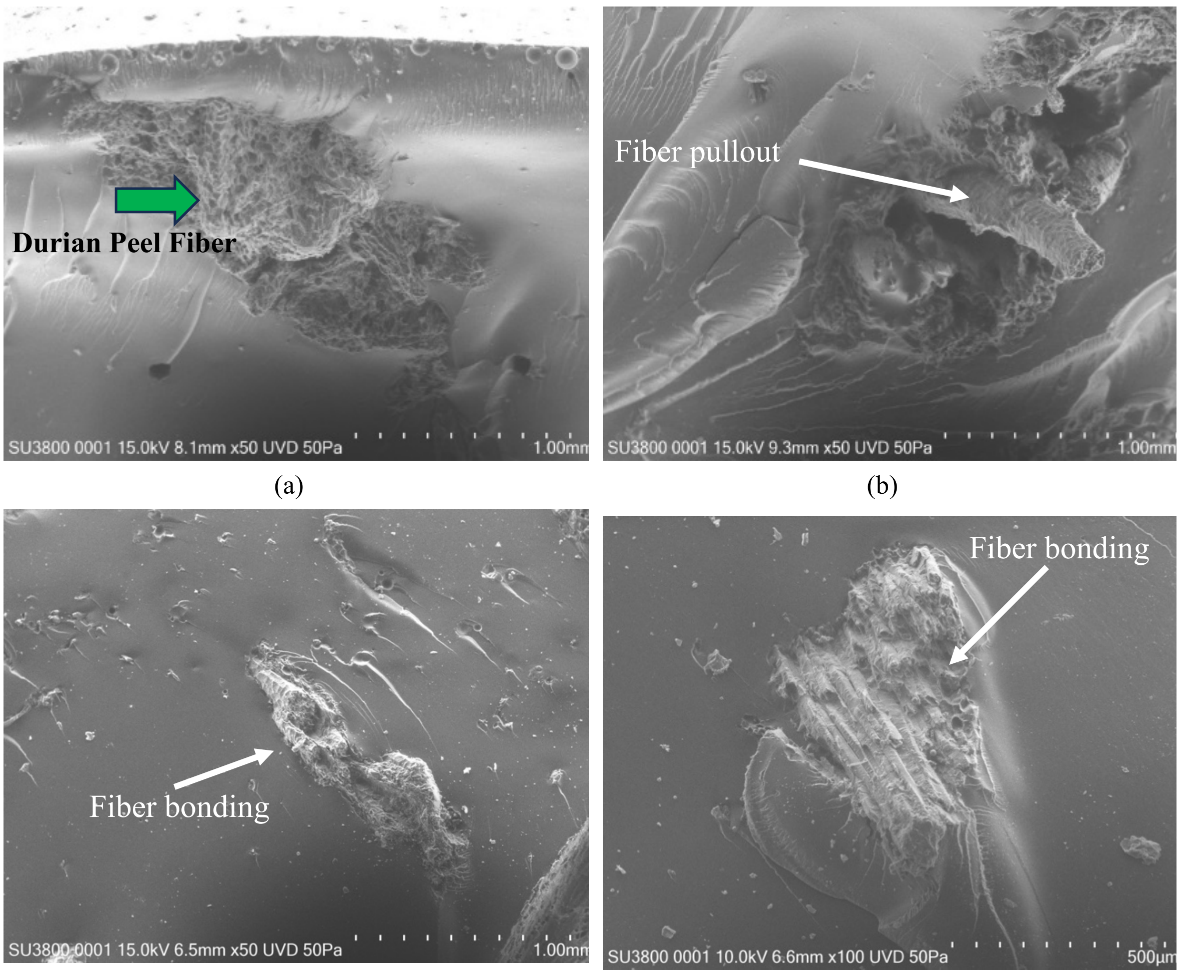
Morphological and structural characteristics of epoxy composite/Durian Peel Fiber (DPF)

The structural morphology (SEM) of the epoxy composite material reinforced with durian peel fibers is presented in **Figures 3** and **4**. From the SEM image results of the EP/DPF-5%Ca material **(Figure 3(d))** shows that the durian peel fiber is compatible with the epoxy resin. On the epoxy-durian peel fiber interface, it is clearly observed that there is no peeling between the resin and the durian fiber, a part of the durian fiber is pulled out to the outside epoxy resin base. Meanwhile, with samples EP/DPF-2%Ca, EP/DPF-3%Ca, there began to be peeling and peeling off of the epoxy-durian shell fiber interface. Especially with the epoxy composite material reinforced with durian peel fibers that have not been treated with lime water in EP/DPF - **Figure 3(a)**, shows that the durian peel fibers are broken on the epoxy resin base when force is applied. The epoxy resin - durian peel fiber surface interface is different from the materials when the durian peel fiber has been modified. However, when increasing the concentration of $Ca(OH)_2$ treatment solution to 6 %, the durian peel fiber-epoxy surface interface was observed **(Figure 4(b))** that the fiber was peeled off from the epoxy resin matrix. Thus, the SEM measurement results of the materials show that the structural morphology measured at the failure surface with the mechanical measurement sample (tensile test sample) shows that the fiber is treated with 5 % mass concentration of solvent. Clear lime solution gives the best structural shape, that is, there is no peeling, the adhesion between fibers and epoxy resin is higher than other materials.

The use of durian peel fibers to reinforce epoxy composite materials has shown positive results, as observed through scanning electron microscope (SEM) images. In summary, the results show good interaction between the durian peel fiber surface and the epoxy resin, with no obvious phase separation at the durian peel fiber-epoxy resin interface. SEM images provide a detailed look at the structure and pattern of the composite material, highlighting that the durian peel fibers and epoxy resin have formed a strong bond. This can enhance the uniformity and uniformity of the material, and enhance its physical and mechanical properties.

The absence of phase separation at the interface between epoxy fiber and durian peel fiber shows that the bonding and interaction process between these 2 components is effective. This increases the load-carrying capacity and uniform properties of the composite material, making it a notable choice for mechanical and construction applications **(Figures 2** and **3)**.

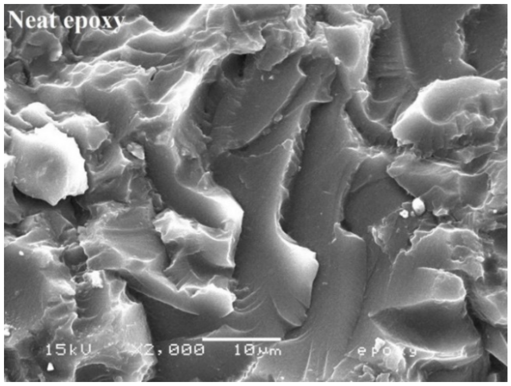
These results provide a positive impetus for the research and development of environmentally friendly and high-performance composite materials, using durian shell fibers as a recyclable resource.



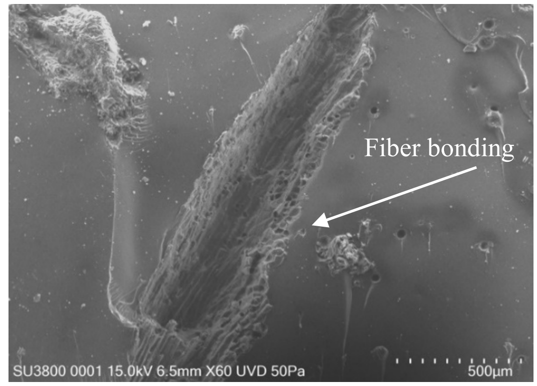
(a) (b)

(c) (d)

Figure 3 SEM image of epoxy nanocomposite materials reinforced with durian peel fibers (DPF), with (a): EP/DPF- Durian fruit peel fibers treated, (b): EP/DPF-3%Ca - Durian fruit peel fibers treated with $Ca(OH)_2$ at a concentration of 3 %, (c): EP/DPF-4%Ca - Durian fruit peel fibers treated with $Ca(OH)_2$ at a concentration of 4 %, (d): EP/DPF-5%Ca - Durian fruit peel fibers treated with $Ca(OH)_2$ at a concentration of 5 %.



(a)



(b)

Figure 4 SEM image of epoxy nanocomposite materials reinforced with durian peel fibers, with (a): Neat Epoxy and (b): EP/DPF-0.1M- Durian fruit peel fibers treated with $Ca(OH)_2$ at a concentration of 6 % (EP/DPF-6%).

When durian peel fibers are treated with $Ca(OH)_2$ - lime solution at different concentrations (3, 4, 5 and 6 %) for 3 days at room temperature, the results from scanning electron microscopy (SEM) images illustrate the transformation of compatibility and adhesion between durian peel fibers and epoxy resin.

SEM images reveal that the level of compatibility and adhesion between durian peel fibers and epoxy resin increases as the concentration of $Ca(OH)_2$ solution rises from 3 to 5 % **(Figures 3(a) - 3(d))**. This phenomenon can be explained by the $Ca(OH)_2$ solution, also known as lime, creating optimal conditions to interact with the surface of durian peel fibers. When durian peel fibers are treated at 6 % $Ca(OH)_2$ concentration, the structural morphology of the material partly shows peeling and peeling, indicating that the bond between the fiber and the epoxy resin is not good, and tends to decreasing direction. At the same time, it also shows poor wetting adhesion compared to materials when fibers are treated at a lower concentration of 5 % $Ca(OH)_2$. This can be explained by the excessive amount of $Ca(OH)_2$ used (excess) leading to a change in the structure of the fiber, which affects the compatibility and adhesion on the epoxy-fiber interface durian peel.

Mechanical properties of epoxy/durian peel fiber composite (EP/DPF)

Tensile strength, flexural strength, compressive strength, and Izod impact strength of EP/DPF composite materials

The mechanical properties of the composite epoxy/durian peel fiber materials were determined in terms of tensile strength, flexural strength, compressive strength and Izod impact strength and are presented in **Figure 5**. From the property results mechanical strength in **Figure 5**, shows that mechanical strengths tend to increase when reinforced with durian peel fibers when chemically treated with $Ca(OH)_2$. The best established strength values are for composite EP/DPF materials, where DPF is chemically treated with 5 % $Ca(OH)_2$ solution concentration. Specifically, tensile strength: 65.68 MPa, durability: 92.11 MPa, compressive strength: 147.38 MPa and Izod impact strength reaches 9.07 kJ/m^2.

This enhanced interaction has increased the material's resistance to bending, highlighting positive mechanical properties. The Izod impact strength has proven to be another crucial property with positive outcomes at a 5 % concentration, achieving a value of 9.07 kJ/m^2. This suggests that the improved interaction between fibers and resin positively contributes to the material's impact resistance. Although there is a slight reduction in compressive strength, reaching 147.38 MPa at a 5 % $Ca(OH)_2$ concentration, this decrease is negligible and remains within an acceptable range.

Overall, the treatment of jackfruit peel fibers with a 5 % $Ca(OH)_2$ solution has significantly contributed to enhancing the mechanical properties of epoxy composite materials, showcasing the efficient potential of this method in reinforcing materials. The process of treating durian peel fibers with $Ca(OH)_2$ solution has significantly improved the impact strength, flexural strength, and tensile strength of the epoxy composite material. Explaining the mechanical properties of EP/DPF material, DPF chemically treated with 5 % $Ca(OH)_2$ solution concentration has higher mechanical strength than the remaining materials, explained as follows: After. According to the discussion in the section on SEM structural morphology **(Figure 2(d))**, observations from the interface between epoxy resin-DPF show strong interaction and adhesion between the fiber and the matrix resin, clearly without separation sudden fading or peeling of layers.

The fracture properties are uniform, no cracks are observed, and no gaps are formed. Thus, by treating DPF fibers with $Ca(OH)_2$ chemical at a solution concentration of 5 %, the fibers achieve the best level of compatibility, forming a structure capable of absorbing force, reducing the risk of breaking destroy materials. The bond between the fiber and the epoxy resin is optimal, the structure is uniform without phase separation, helping to enhance mechanical strengths such as tensile, bending and impact strength. In summary, the surface treatment of durian peel fibers with $Ca(OH)_2$ solution, especially at a 5 % concentration, not only improved the mechanical properties of the epoxy composite material but also optimized the structure and interaction between components, making it a promising choice for various applications requiring high mechanical properties.

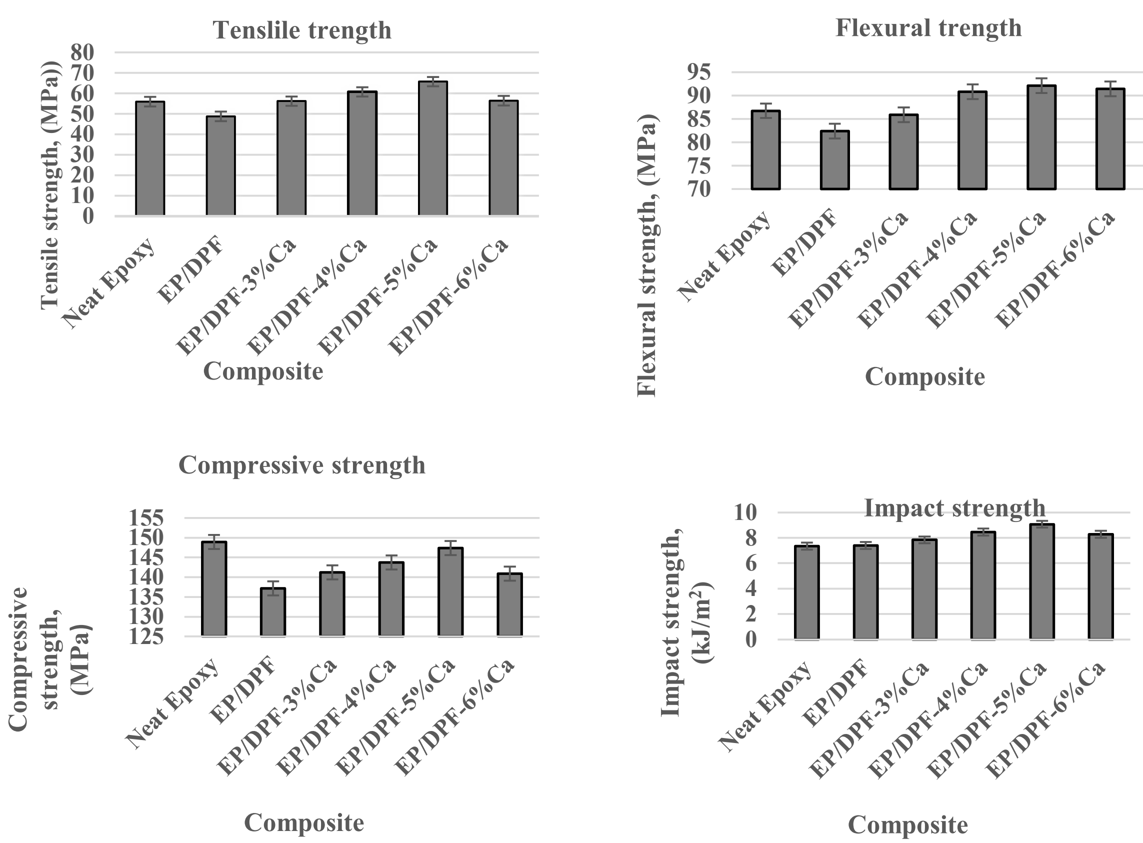


Figure 5 Mechanical properties of epoxy composite materials reinforced with durian peel fibers (DPF) treated with $Ca(OH)_2$ at different concentrations.

The results from this study on EP/DPF composites demonstrate favorable mechanical properties, with a tensile strength of 65.68 MPa, a flexural strength of 92.11 MPa, a compressive strength of 147.38 MPa, and an impact strength of 9.07 kJ/m². When compared to previous studies, such as that of Kushwaha and Kumar [25], which reported tensile strengths ranging from 87 - 135 MPa and flexural strengths from 92 - 154 MPa, the composites in this study show a competitive tensile strength, although still below the upper range reported. Their findings also indicate good impact resistance, with values between 8.95 and 30.25 kJ/m², which suggests that there is still room for improvement in the impact strength of our composite.

In contrast, the study by Vidyashri *et al.* [26] indicates lower tensile strength values, ranging from 20.43 to 42.86 MPa. This highlights the superior performance of our composite, particularly in tensile strength and flexibility, which can be attributed to the specific treatment and formulation used in this research. Furthermore, the results of Batu and Lemu [27] demonstrate tensile strengths ranging from 16 to 35 MPa and flexural strengths from 35 to 68 MPa, which are significantly lower than those found in our study.

This reinforces the effectiveness of the chemical treatment employed in our composite, as it surpasses the mechanical properties of composites made from false banana and glass fibers. On the other hand, the research by Islam *et al.* [28] shows a wider range of tensile strength from 65 to 162 MPa and flexural strength between 145 and 180 MPa, indicating that while our tensile strength is at the lower end of their spectrum, the compressive strength of 147.38 MPa achieved in this study is quite impressive and demonstrates the material's robustness. Their impact strength results, which range from 7 to 17 kJ/m², also suggest that our composite exhibits enhanced performance in this area.

In summary, the findings from this study highlight the competitive nature of the EP/DPF composite, particularly with the green chemistry approach using $Ca(OH)_2$ for fiber treatment, as opposed to traditional chemicals like NaOH. This not only improves mechanical properties but also emphasizes environmental sustainability. The results align favorably with the existing literature, showcasing the potential for further optimization and application of this composite in various fields.

Fracture toughness (K_{IC}) of composite EP/DPF

Fracture toughness is an important indicator in the evaluation and development of composite materials for industrial and engineering applications. It not only reflects the material's ability to withstand mechanical impacts but can also be used to assess and optimize the production process, thereby enhancing the quality and performance of the final product. Understanding fracture toughness helps engineers select suitable materials and design safer, more efficient structures.

When studying the fracture toughness of epoxy composite materials reinforced with durian husk fibers at different concentrations, the results show a significant change in fracture toughness as the fiber content increases. Specifically, from **Figure 6**, it is evident that as the fiber content increases from 3 to 5 % by weight, the fracture toughness of the material increases significantly, reaching a maximum value of 7.81 MPa.$m^{1/2}$ at 5 % fiber content. However, when the fiber content continues to increase to 6 %, the fracture toughness begins to decrease. The increase in fracture toughness at the 5 % fiber content can be explained by considering the role of the fibers in the composite structure. Durian husk fibers not only provide stiffness but also enhance the load-bearing capacity of the epoxy resin. When the fibers are added to the epoxy resin, they create a stronger network of bonds, which helps to distribute and absorb impact energy more effectively, thereby improving the fracture toughness.

At a fiber content of 5 %, it can be said that the ratio between fibers and epoxy resin achieves an optimal balance. At this point, the fibers can fully exert their reinforcing capabilities without compromising the properties of the resin matrix. However, when the fiber content is increased to 6 %, there is a possibility of stress concentration, where the fibers may not interact effectively with the resin, leading to a reduction in toughness. Additionally, increasing the fiber content may introduce inhomogeneities in the structure, weakening the adhesion between the fibers and the resin, and thus diminishing the overall performance of the material. Therefore, this study highlights that optimizing the fiber content in composite materials is crucial for achieving the best mechanical properties, particularly fracture toughness. The results indicate that a fiber content of 5 % by weight of durian husk fibers is optimal for achieving the highest fracture toughness in epoxy composite materials.

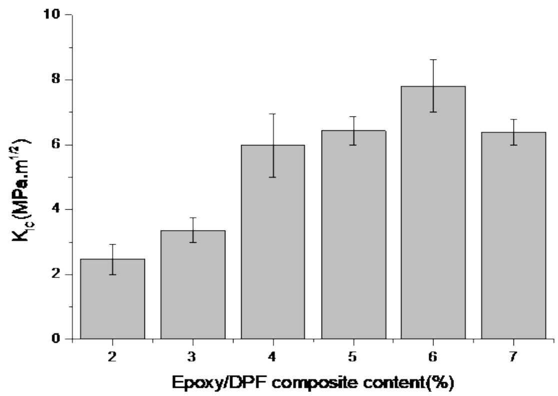


Figure 6 Influence of EP/DPF content on the fracture toughness of composite materials.

In this study, the fracture toughness (K_{IC}) of epoxy composite materials reinforced with durian husk fibers shows a marked improvement with increasing fiber content. Specifically, as the fiber content increases from 3 to 5 % by weight, the fracture toughness reaches a maximum value of 7.81 MPa.m$^{1/2}$ at 5 % fiber content. This significant enhancement indicates that optimizing fiber content can greatly influence the material's resistance to crack propagation. When comparing these findings to the work of Islam *et al.* [28], which demonstrates that the fracture toughness (K_{IC}) of hemp/epoxy composites is also improved through chemical treatment of fibers with NaOH, reaching a maximum value of 5 MPa.m$^{1/2}$, it is evident that the durian husk fiber composites outperform the hemp composites in terms of fracture toughness.

The difference in performance could be attributed to several factors, including the inherent properties of the durian husk fibers, which may provide better interfacial bonding with the epoxy matrix, or the specific treatment methods used for each type of fiber. While Islam *et al.* [28] highlight the effectiveness of alkali treatment in enhancing the mechanical properties of hemp fibers, the results from this study suggest that not only does fiber treatment matter, but the choice of fiber type and its concentration play a critical role in optimizing fracture toughness.

Overall, the findings from this study illustrate the potential of durian husk fibers as a strong candidate for reinforcement in epoxy composites, especially considering their superior fracture toughness compared to those reinforced with chemically treated hemp fibers. This highlights the importance of exploring various natural fibers and treatment methods to further enhance the mechanical properties of composite materials.

Flame retardant properties of epoxy composite materials reinforced with durian peel fibers treated with $Ca(OH)_2$ at different concentrations

An investigation into the flame-retardant properties of durian peel fiber-reinforced epoxy composite materials is presented in **Figure 7**. The results from **Figure 7** indicate an enhancement in the combustion characteristics of the material for samples where durian peel fibers were treated with $Ca(OH)_2$, particularly when treated with a mass concentration of 5 % $Ca(OH)_2$. In this case, the LOI reached 21.9 %, classifying the material as flame-retardant.

Reinforcing composite materials with plant-based fibers, such as durian rind fibers, can improve the flame retardant properties of the material. This reinforcement is explained by several factors. First, the lignin content in durian rind fibers naturally possesses flame-resistant properties, playing a role in increasing the material's fire resistance. Second, during combustion, plant fibers generate a layer of carbonization, acting as a barrier to heat and gas transfer, reducing the rate of combustion and the spread of fire. Third, the crystalline structure of plant fibers can create a protective layer, decreasing the rate of combustion and increasing flame resistance. Fourth, the water absorption capability of plant fibers can cool and slow down the combustion process. Finally, the processing of plant fibers can enhance the interaction between the fibers and the resin matrix, creating a more effective fire-resistant system.

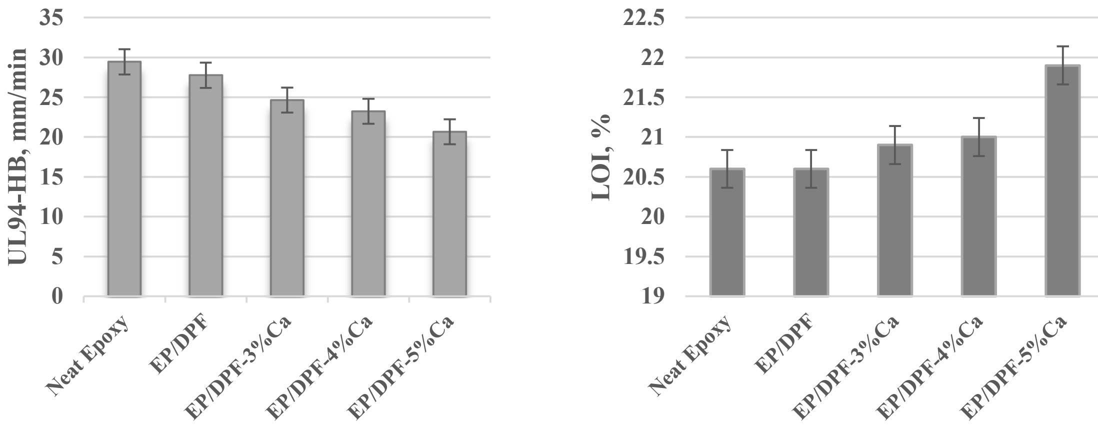


Figure 7 Flame retardant properties of epoxy composite materials reinforced with durian peel fibers treated with $Ca(OH)_2$.

In the research by Hasan *et al*. [29], the successful incorporation of lignocellulosic and carbon fibers into epoxy resin resulted in enhanced flame-retardant characteristics. Their findings underscore the effectiveness of hybrid composites in improving fire resistance, showcasing the potential of combining different fiber types for better performance. In contrast, Kurniasih *et al*. [30] focused on Agel leaf fiber-epoxy composites modified with carbon powder, achieving a reduction in burn rate by 42.624 mm/s and an ignition time of 17.33 s. These results illustrate significant improvements in flammability characteristics, reflecting the efficacy of their specific modifications in enhancing fire resistance.

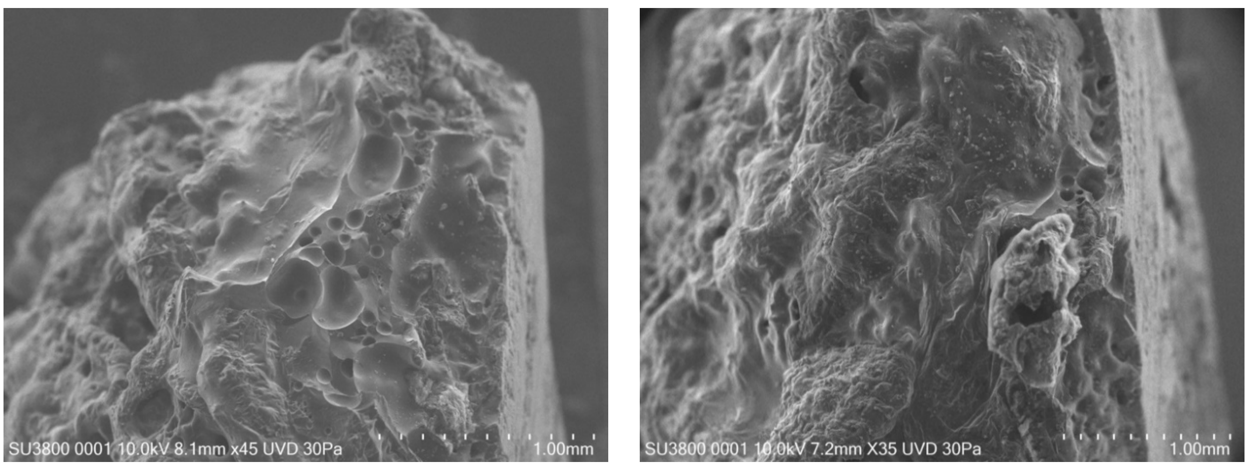
Our study on durian peel fibers treated with 5 % $Ca(OH)_2$ presents noteworthy findings as well. The LOI reached 21.9 %, classifying the material as flame-retardant, alongside a burning rate of 20.66 mm/min according to UL-94HB standards. The comparatively higher LOI suggests that the durian peel fibers not only exhibit enhanced flame resistance but also demonstrate an effective approach to achieving fire retardancy through a simple, environmentally friendly treatment method. The differences observed in flame-retardant properties among these studies may stem from the unique characteristics of the fibers used and the specific treatment methods applied. While Hasan *et al*. [29] focused on hybridization to achieve fire resistance, Kurniasih *et al*. [30] improved the properties through the addition of carbon powder, our approach emphasizes the potential of natural fibers, particularly from durian peels, treated with green chemistry solutions like $Ca(OH)_2$. This indicates that not only can natural fibers be effective in flame-retardant applications, but they can also be enhanced through eco-friendly processing methods, making them viable for sustainable material development.

Overall, these findings support the exploration of durian peel fibers as a promising alternative in the field of flame-retardant composites, showcasing their competitive performance compared to other natural and hybrid fiber options. This emphasizes the importance of further investigating various natural fibers and their treatment methods to develop sustainable, high-performance composite materials for diverse applications.

Analysis of carbon structure after LOI method

Figure 8 illustrates the surface structure of the charred material after applying the LOI method for EP/DPF-5%Ca (durian peel fiber treated with 5 % $Ca(OH)_2$) and EP/DPF-6%Ca (durian peel fiber treated with 6 % $Ca(OH)_2$). The results reveal the presence of porous regions, particularly on the surface of EP/DPF-5%Ca, while the majority of the area consists of solid carbon structures.

Detailed observation through scanning electron microscopy (SEM) indicates that the charred surface lacks cracks or gaps, instead showcasing the formation of robust carbon blocks, akin to biochar. When DPF fibers are chemically treated with $Ca(OH)_2$ at a solution concentration of 5 %, the material structure achieves a strong, tight structure, with the strongest interaction between the fiber and the epoxy resin. Strong adhesion to each other forms a well-structured material system, thus improving mechanical properties as well as fire resistance properties. Because when the structure is dense, interactive, and has high adhesion, defects will not form, thus reducing the degree of ignition. That's why when a layer of ash (coal) is formed, it has a durable structure that acts as a shield to prevent contact between the material and the fire source (fire source) and oxygen.



(a) (b)

Figure 8 SEM image of the char part of the material after experimental combustion using the LOI method: (a)-EP/DPF-5%Ca and (b) EP/DPF-6%Ca.

In the raw material extraction phase, durian peel fibers are a byproduct of the food processing industry, which helps reduce waste without the need for new resource extraction. In contrast, synthetic plastics require the extraction of petroleum, leading to pollution and contributing to climate change.

During the processing phase, durian peel fibers are treated with environmentally friendly chemicals like $Ca(OH)_2$, minimizing harmful emissions and waste, whereas the production of plastics typically involves high energy consumption and the use of hazardous chemicals. In terms of use, composites made from durian peel fibers can exhibit mechanical properties equivalent to or superior to those of synthetic plastics, with a longer lifespan that reduces the frequency of replacement and overall waste.

Finally, in the end-of-life phase, durian peel fibers possess good biodegradability, helping to mitigate environmental pollution, while synthetic plastics often do not decompose, leading to waste accumulation. Thus, using durian peel fibers not only provides mechanical advantages but also contributes significantly to sustainable development and environmental protection. This comprehensive assessment emphasizes the overall positive environmental impact of adopting durian peel fibers over traditional materials, addressing the concerns raised by reviewers regarding sustainability and environmental considerations.

Conclusions

This study investigated the chemical treatment of fibers from durian fruit peel using $Ca(OH)_2$ at concentrations of 3, 4, 5 and 6 % for 3 days at room temperature. The results indicated that a 5 % $Ca(OH)_2$ solution yielded the best mechanical properties: Tensile strength of 65.68 MPa, durability of 92.11 MPa, compressive strength of 147.38 MPa, and Izod impact strength of 9.07 kJ/m². Additionally, the fire resistance was notable, with an LOI index of 21.9 % and a burning rate of 20.66 mm/min according to UL-94HB standards.

Structural morphology analysis via SEM revealed that the chemical treatment significantly enhanced the interaction between durian peel fibers and epoxy resin, resulting in a robust, well-adhered epoxy-fiber interface. This suggests that the EP/DPF composite material is a promising green alternative for applications in construction, automotive, and transportation industries.

However, the study has some limitations, including the scope of concentrations tested and the need for long-term performance assessments of the composites under varying environmental conditions. Future research should explore a broader range of chemical treatments and concentrations, as well as the effects of additives or blending with other natural fibers to enhance the properties of the composite materials further. Additionally, conducting life cycle assessments could provide valuable insights into the environmental benefits of using durian peel fibers in industrial applications.

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